PB86-190071

Methodology for Designing Air Quality Monitoring Networks: 2. Application to Las Vegas, Nevada, for Carbon Monoxide

(U.S.) Environmental Monitoring Systems Lab.
Research Triangle Park, NC

1986

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/J-86/036	2.
3. RI PB86-190071	
4. TITLE AND SUBTITLE METHODOLOGY FOR DESIGNING AIR QUALITY MONITORING NETWORKS: II. Application to Las Vegas, Nevada, for Carbon Monoxide (Journal Version)	5. REPORT DATE 1986
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) J.L. McElroy, J.V. Behar; T.C. Meyers, M.K. Liu	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Monitoring Systems Laboratory, U.S. EPA P.O. Box 15027, Las Vegas, NV 89114 Systems Applications, Inc., San Rafael, CA 94903	10. PROGRAM ELEMENT NO. A104 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Monitoring Systems Laboratory-LV, NV Office of Research & Development U.S. Environmental Protection Agency Las Vegas, NV 89114	13. TYPE OF REPORT AND PERIOD COVERED Journal Reprint 14. SPONSORING AGENCY CODE EPA/600/07

15. SUPPLEMENTARY NOTES

Environmental Monitoring and Assessment, 6:13-34, January 1986

16. ABSTRACT

An objective methodology presented in a companion paper (Liu et al., 1986) for determining the optimum number and disposition of ambient air quality stations in a monitoring network for carbon monoxide is applied to the Las Vegas, Nevada, area. The methodology utilizes an air quality simulation model to produce temporally-varying air quality patterns for each of a limited number of meteorological scenarios representative of the region of interest. These air quality patterns in turn serve as the data base in a two-step procedure for the identification and ranking of the most desirable monitoring locations (step 1) and the removal of redundancies in spatial coverage among the desired locations (step 2).

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 24
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This article documents research that was conducted under the auspices of the U.S. Environmental Protection Agency (USEPA). As an arm of the government, the USEPA has a paid up, non-exclusive, irrevocable, worldwide license to reproduce, prepare derivative works, and distribute to the public all of the material contained herein, and to grant others acting on its behalf the right to do so. The USEPA grants to the National Technical Information Service, Department of Commerce, the right to act as its agent in the distribution of this material.

EPA/600/J-86/036
JOURNAL ARTICLE

METHODOLOGY FOR DESIGNING AIR QUALITY MONITORING NETWORKS: II. APPLICATION TO LAS VEGAS, NEVADA, FOR CARBON MONOXIDE

J. L. McELROY, J. V. BEHAR

U.S. Environmental Protection Agency Environmental Monitoring Systems Laboratory, Las Vegas, NV 89114, U.S.A.

T. C. MEYERS, and M. K. LIU

Systems Applications, Incorporated, San Rafael, CA 94903, U.S.A.

(Received 9 May, 1984)

Abstract. An objective methodology presented in a companion paper (Liu *et al.*, 1986) for determining the optimum number and disposition of ambient air quality stations in a monitoring network for carbon monoxide is applied to the Las Vegas, Nevada, area. The methodology utilizes an air quality simulation model to produce temporally-varying air quality patterns for each of a limited number of meteorological scenarios representative of the region of interest. These air quality patterns in turn serve as the data base in a two-step procedure for the identification and ranking of the most desirable monitoring locations (step 1) and the removal of redundancies in spatial coverage among the desired locations (step 2.)

The performance of the air quality simulation model, a key element in the design methodology, was evaluated in the Las Vegas area in a special field measurement program. In the Las Vegas demonstration for carbon monoxide, 19 stations covering concentration maxima and 3 stations covering background concentrations in rural areas were identified and ranked. A 10-station network, for example, consisting of 7 stations for peak average concentrations and 3 stations for background concentrations, was selected for a desired minimum detection capability of 50% of concentration variations. Networks with fewer stations would be selected if smaller minimum detection capabilities of concentration variations are acceptable, and vice versa. Background stations could, of course, be deleted for networks with the sole purpose of discerning peak concentrations.

1. Introduction

In a companion paper, an objective methodology was presented for determining the optimum number and disposition of ambient air quality stations in a monitoring network (Liu *et al.*, 1986). This paper describes application of the methodology as a demonstration in the metropolitan Las Vegas, Nevada, area for the relatively inert pollutant carbon monoxide (CO). The procedures and tools developed for the siting methodology are applicable however, to chemically reactive as well as chemically inert pollutants.

The proposed methodology uses climatological information and an air quality simulation model. First, the climatological information is used to generate a limited number of meteorological scenarios representative of the region of interest. For each of the

Although the research described in this article has been funded wholly or in part by the United States Environmental Protection Agency through Contract No. 68-03-2446 to Systems Application, Inc., it has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Environmental Monitoring and Assessment **6** (1986) 13–34
© 1986 *by D. Reidel Publishing Company.*
NTIS is authorized to reproduce and sell this report. Permission for further reproduction must be obtained from the copyright owner.

scenarios, the air quality simulation model is employed to produce the corresponding temporally-varying air quality patterns. The air quality patterns serve as the primary data base in a two-step procedure for determining the optimal monitoring network. In the first step, the air quality patterns are collapsed into a single composite pattern through the use of the figure-of-merit (FOM) concept. For a specific time interval and location, the FOM is determined as the sum over the meteorological scenarios of the products of the pollutant concentrations and the associated probabilities of occurrence. The identification and ranking of the most desirable monitoring locations are achieved using the resultant FOM fields. In the second step, the network configuration is determined on the basis of the concept of a sphere of influence (SOI). The SOIs are dictated by a cutoff value in the spatial correlation coefficients between the pollutant concentrations at the monitoring stations identified and the corresponding concentrations at neighboring locations in the region. This cutoff value is related to an estimate of concentration variations that can be accounted for by a given monitoring station. The minimum number of monitoring stations required is then determined by deleting lower-ranked stations whose SOI overlap the SOI of higher-ranked stations and whose SOIs provide nonoverlapping coverage of less than some fixed percentage of the coverage of the SOI of the higher-ranked stations.

The practice of using simulated concentration distributions generated by an air quality model was adopted in this study because few regions or urban areas have a monitoring network in operation over a sufficient time interval and of sufficient density to yield the requiste concentration distribution for network design. However, of necessity, it would be important to validate or calibrate the air quality model for the area of interest. These efforts are discussed in this paper as part of the demonstration of the proposed siting methodology to the metropolitan Las Vegas area.

2. A Description of the Study Area – Las Vegas Valley in Nevada

The Las Vegas Valley is a reasonably isolated desert community with a population of over 500 000 people. The valley, located in Clark County in southern Nevada, is bounded by the Sheep Range and Las Vegas Range to the north, the Spring Mountains to the west, Frenchman and Sunrise Mountains to the east, and the McCullough Range to the south (Figure 1). These mountains, averaging about 1 km above the valley floor, impart a bowl shape to the modeling region with passes to the northwest, southwest and southeast. The floor of the valley slopes gently from west to east, from 900 m above Mean Sea Level (MSL) on the west to approximately 500 m MSL in the Las Vegas Wash area on the east-southeast side. To the east of the Las Vegas Wash, the terrain gently rises again. Because the urban area of Las Vegas consists of vacant desert scattered among residential developments, the population is distributed over a larger area then many other urban communities of equivalent population. To serve this large area, a limited access interstate highway traverses the city, and major highways criss-cross the valley. A large grid of four-and six-lane arterial streets and an intermeshed network of secondary roadways accommodate local traffic.

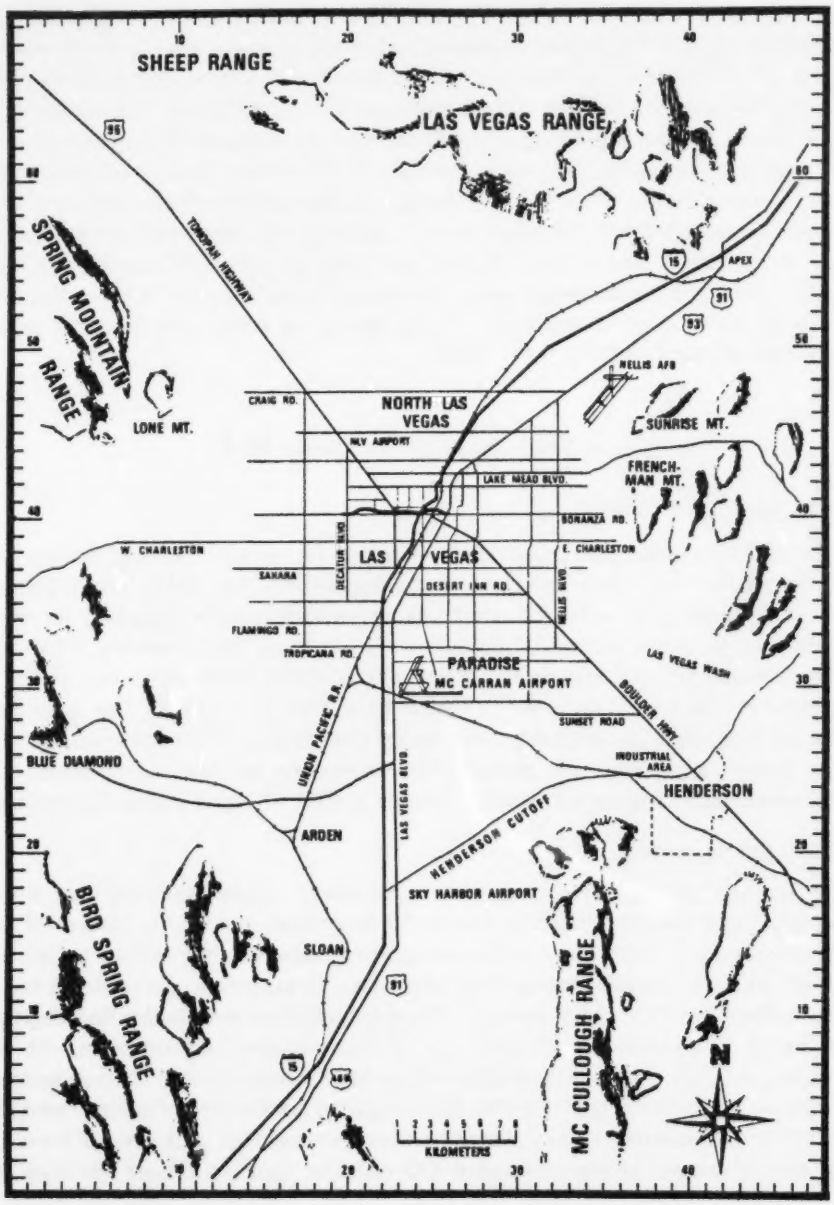

Fig. 1. Map of the Las Vegas Valley.

It should be noted that the Las Vegas Valley is currently a non-attainment* area for the pollutant CO. The highest concentrations of CO typically occur in the downtown area and the low-lying or wash areas in the eastern and southeastern portions of the valley, following the morning and especially the evening traffic peak. Climatologically, the periods experiencing the highest concentrations, exceeding the National Ambient Air Quality Standards (NAAQS) are the late fall and early winter. The times of peak traffic, which generate nearly all the CO in the valley, coincide with periods of minimal pollutant dipersal associated with the existence of a nocturnal radiation temperature inversion during this time of the year. Such an inversion dissipates most slowly the first few hours after sunrise and forms around sunset. Consequently, highest short-term (on the order of a few hours) concentrations can also be expected to occur more frequently during this time of year (McElroy *et al.*, 1978).

3. Validation of the Air Quality Model

3.1. Air quality model

The air quality model used to provide the data base for use with the siting methodology is the 'airshed' model developed by Systems Applications, Inc. (SAI). The SAI model is an Eulerian grid model for which the appropriate species equations for mass continuity are solved numerically in finite difference form. The theoretical framework for the model is discussed in detail in Reynolds *et al.* (1973, 1974) and Roth *et al.* (1974) and the mechanics and operation of the model in Ames *et al.* (1978). This model was chosen primarily because it can provide spatial distributions of both inert pollutants for the present application and photochemical pollutants for future applications and because it has undergone considerable scrutiny by EPA – hence it was readily available.

3.2. Modeling region

Because the Las Vegas Valley represents a relatively isolated urbanized area, it was assumed that boundary conditions could be determined more easily because of this relative isolation. That is, one could reasonably expect that very little pollutant of interest would enter the modeling region from other areas. Consequently, the modeling region was defined as a 48 × 70-km area extending to the ridgelines surrounding the valley (see Figure 1). The region was divided into 1 × 1-km squares commensurate with the resolution of pollutant emission data and consistent with reasonable computational requirements for the air quality model. It is recognized that the scale of natural variability of CO in the immediate vicinity of major emission sources like roadways is of the order of tens of meters. However, detailed CO emission data on a scale less than the

* A 'non-attainment area' is an area which is shown by monitoring data or which is calculated by air quality modeling (or other methods determined by the Administrator of the EPA to be reliable) to exceed any National Ambient Air Quality Standard (NAAQS) for a given pollutant. For CO the NAAQS are 10 mg m^{-3} (9 ppm) maximum 8 hr concentration (primary) and 40 mg m^{-3} (35 ppm) maximum 1 hr concentration not to be exceeded more than once per year (secondary).

prescribed model resolution were not available and ambient monitoring sites are not typically located in close proximity to major sources.

3.3. Emissions Inventory

Emissions data for CO were inventoried within the 48 x 70-km area divided into 1 x 1-km squares. Emissions from point sources (electric power generation plants and industrial plants), area sources (space heating), and mobile sources (railroads, aircraft, and road vehicles) were determined for each hour of the day within each 1-km grid square. Light duty vehicle emissions have been shown to depend on ambient temperatures. These emissions account for 80% of the total inventory on a daily basis and must be adjusted to reflect different ambient temperature conditions. Thus, an emissions inventory was developed specifically for each day simulated; however, since only weekday traffic data was available, only weekdays (Monday–Friday) were simulated. Seasonal variations were observed and taken into account. The emissions inventory was developed from information provided by State and local agencies, local industries and utilities, and the National Emissions Data Service data bank using AP-42 and its supplements as a guide (U.S. EPA, 1976).

3.4. Field measurement program

Data for the model validation effort were acquired through a special field measurement program during late fall 1975 and winter 1975–76. Based on predominant synoptic scale and locally-induced wind patterns (e.g., upslope and downslope winds), topography, land use, and traffic data, a total of 25 sites were selected to provide data for model verification and supplementary data used in the design of a CO monitoring network (Figure 2).

Because of the cooperative arrangement with the local agencies monitoring in the valley, only new sites required to supplement those existing were maintained by the U.S. Environmental Protection Agency (EPA). In addition, wind speed, wind direction, cloud cover, and temperature data from the National Weather Service at McCarran International Airport were utilized. Continuous measurements of CO were made at 9 locations and of wind speed and direction and air temperature near the ground at 14 locations (Figure 2); air temperatures only were monitored at 4 additional sites. During intensive sampling periods, measurements of winds aloft were made at two sites with single theodolite observations of 30 g pilot balloons. Also, vertical spirals with an instrumented helicopter yielded profiles of air temperature and dewpoint temperature at several locations in the Las Vegas Valley during intensive sampling periods. Details of the sampling program including the instrumentation used are contained in McElroy *et al.* (1978).

3.5. Comparison of predicted and measured CO concentrations

The SAI model was exercised, utilizing data collected during the field program, for six days in the Las Vegas Valley. Comparisons were made of model predictions and field measurements both on a point-by-point and a spatial and temporal distribution basis.

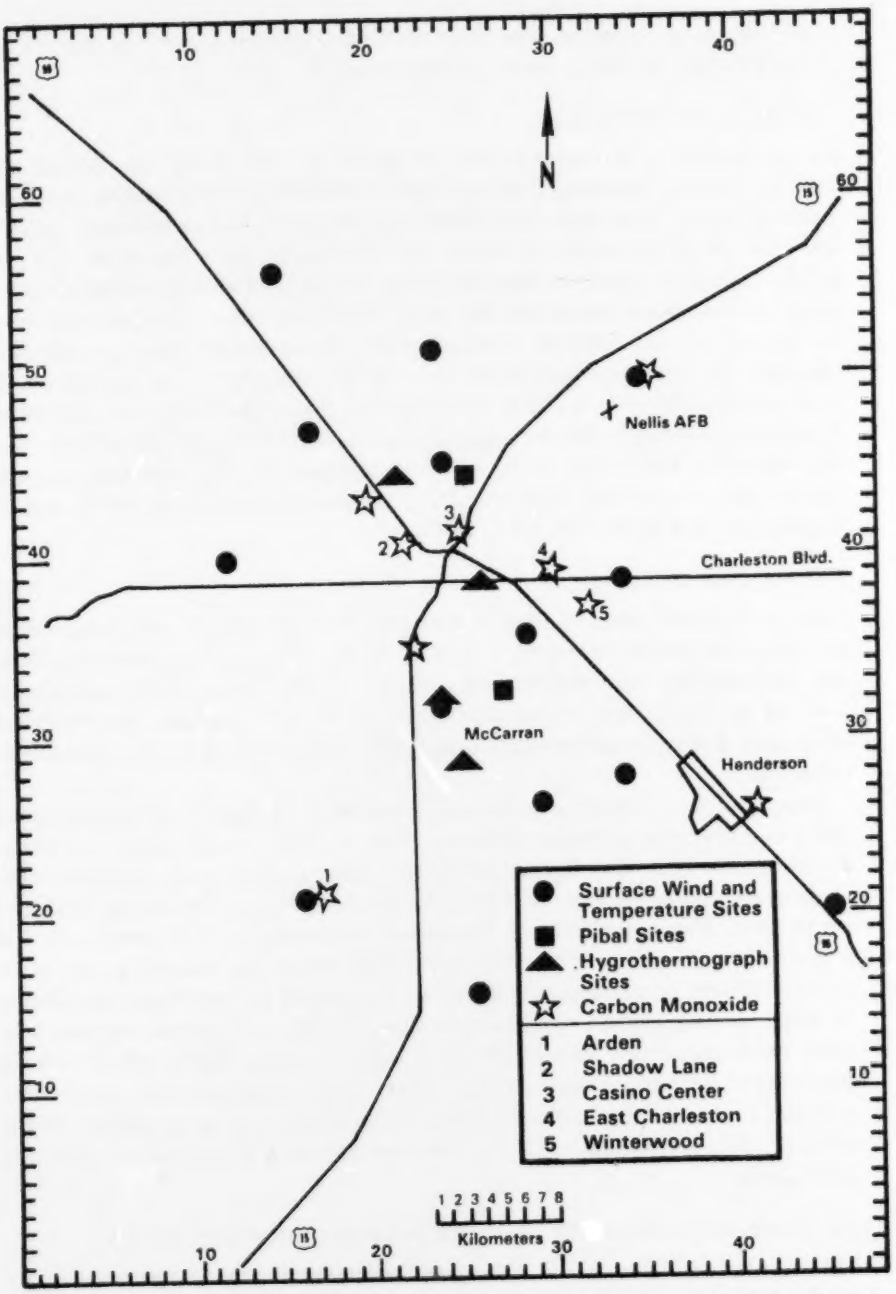

Fig. 2. Carbon monoxide and meteorological measurement sites. (Data for numbered sites shown in Figures 3 and 4).

The point-by-point comparisons are summarized in Table I. Linear correlation coefficients and regression parameters are presented for 1-hr averaged CO data for the six days of the validation study independent of time of day or location. The table shows that the hourly averaged point-by-point comparison between predictions and measurements of the stations taken collectively yielded linear correlations between 0.7 and 0.9 for five of the six validation dates.*

Results of past model validation studies indicate that point-by-point comparisons between pollutant predictions and measurements on an annual or seasonal basis generally result in linear correlation coefficents between about 0.6 and 0.9 (e.g., Koch and Thayer, 1972; Slater and Tikvart, 1974). Limited results are available on hourly comparisons. Those for sulfur dioxide have reported linear coefficients between 0.2 and 0.6 (e.g., Koch and Thayer, 1972; Shirr and Shieh, 1974). Johnson *et al.* (1973) reported coefficients for CO between 0.4 and 0.7 but utilized monitoring sites in the immediate vicinity of roadways and included a microscale submodule for specific microscale effects. Liu *et al.* (1976b) reported coefficients for CO in the range of 0.6 and 0.8 for models finely tuned to a specific metropolitan area. Thus, the comparisons between predictions and measurements on a point-by-point basis for the present study are at least as good as those presented in the literature.

TABLE I

Statistical comparison of predicted and measured CO concentrations

Day	Number of data points	Correlation coefficient	Slope	Intercept (ppm)
Dec. 3, 1975	92	0.76	1.62	−1.23
Dec. 4, 1975	91	0.73	0.91	0.26
Jan. 14, 1976	79	0.74	1.09	0.02
Jan. 16, 1976	67	0.42	0.48	0.78
Jan. 21, 1976	83	0.91	1.22	−0.87
Jan. 22, 1976	92	0.77	0.99	−0.41

Examples of temporal variations of the predicted and measured CO concentrations are compared for four measurement sites in each of Figures 3 and 4. The Arden site was chosen to represent model predictions at remote monitoring locations, and the remaining sites reflect predictions and measurements at areas under the influence of the urban CO emissions (see Figure 2). These figures illustrate that for most of the validation dates, and at most of the measurement sites, the trends of the predicted concentrations follow closely the trends of the measurements. As expected from the results in Table I,

* Since the conduct of this study the air quality model was exercised for January 16, 1976, using a diagnostic complex terrain wind field model (Liu and Yocke, 1980) to develop the wind field for it instead of the normally-used objective analysis technique. With this modification, the linear correlation coefficient increased to 0.77 and the slope became near unity.

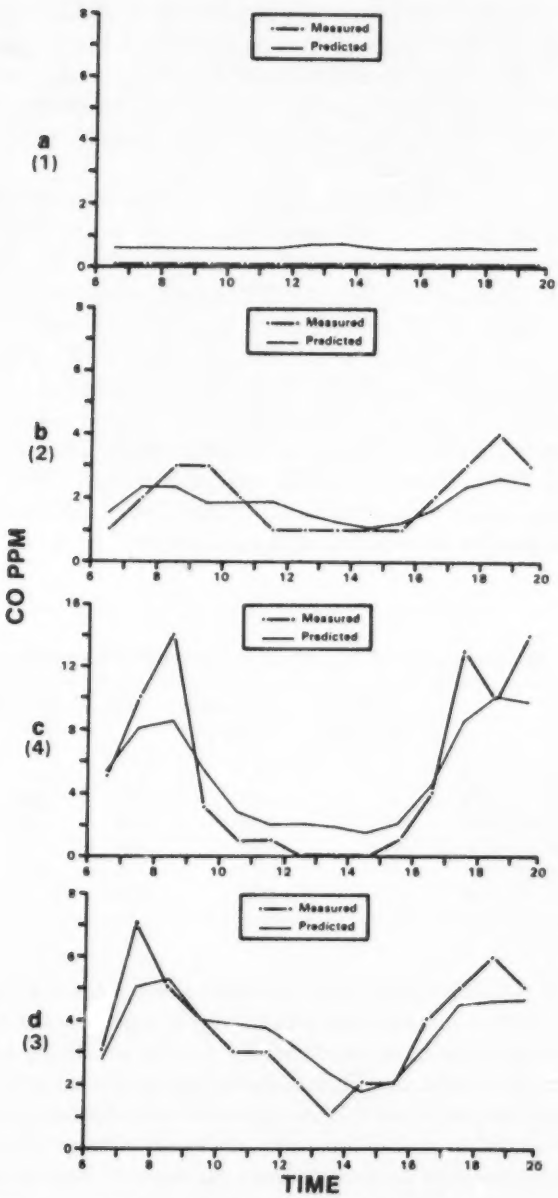

Fig. 3 Predicted and measured CO concentrations at selected sites near Las Vegas on January 21, 1976. (a) Arden (1) (b) Shadow Lane (2) (c) East Charleston (4) (d) Casino Center (3). Numbers in parentheses refer to site locations delineated in Figure 2.

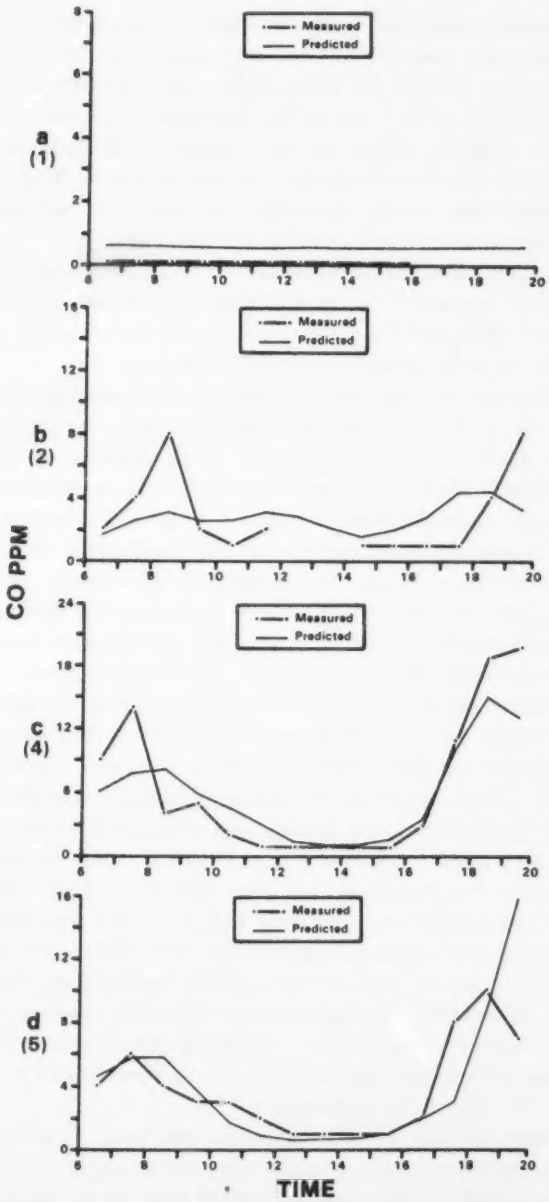

Fig. 4. Predicted and measured CO concentrations at selected sites near Las Vegas on January 22, 1976 (a) Arden (1) (b) Shadow Lane (2) (c) East Charleston (4) (d) Winterwood (5). Numbers in parentheses refer to site locations delineated in Figure 2.

the magnitudes of the predicted minima are close to the minima of the measurements, but the predicted and measured maxima do not compare as well. This is especially true in the downtown area such as at Casino Center (which experiences the highest traffic peaks) and secondarily in the vicinity of the Las Vegas Wash, such as at Winterwood or perhaps East Charleston (Figure 2). Such a weakness in the prediction of absolute peak concentrations may imply unresolved microscale effects. Also, the magnitude of traffic and hence traffic-related emissions may have been underestimated in the emissions inventory for those peak periods (Naylor, 1984).

The figures indicate that the highest measured CO values occur as a result of the evening traffic peak and in the vicinity of the Las Vegas Wash. Since this is an area of convergence for nighttime drainage flow, pollutants are expected to accumulate there resulting in high values following the evening traffic peak.

Spatial distributions of predictions and measurements are not presented here (See McElroy *et al.*, 1978). However, they show that the monitoring stations located in the downtown and wash areas often experience strong gradients in the predicted CO concentration fields. Also, when the predicted concentrations exceed about 10 parts per million (ppm) very sharp gradients usually are found in the central city area. Such gradients suggest that slight uncertainties in the specification of the windfield and apportioning of the emissions, or that subgrid scale processes could greatly affect comparison for these locations. However, the diagrams show that the model usually does well in predicting the general location of hot spots or local maxima.

A detailed study of the air quality model to determine the effect of uncertainties in the input parameters was not conducted as part of the present model validation effort. Such uncertainties may be in the data themselves or in the interpolation routines utilized to prepare the data for use with the model. However, a study on this subject was carried out by Liu *et al.* (1976a) using an earlier version of the model with data appropriate for the Los Angeles metropolitan area. In the study, wind speed, vertical eddy diffusivity, mixing depth, or pollutant emission rate was varied within its expected range of uncertainty with the other parameters kept at specified base values. The relative changes in CO concentrations associated with these variations were then determined through model simulations for a specific data base in the area. The results were evaluated in terms of deviations from areawide averages of CO concentrations. Qualitatively and in a relative sense, the simulated CO values were most sensitive to changes in wind speed, less sensitive to changes in mixing depth and pollutant emission rates, and least sensitive to changes in the vertical eddy diffusivity. For further details on the study, the paper by Liu *et al.* (1976a) should be consulted.

Since agreement between predicted and measured values is good for most of the examined cases, and since the discrepancies can often be accounted for based on either microscale phenomena and uncertainties in input data, the air quality model appears to be adequate for its proposed use in this study – i.e., providing an air quality data base, generated under a variety of meteorological conditions, for exercising the siting methodology in the Las Vegas Valley as a demonstration of the proposed network design.

4. Application of the Siting Methodology

4.1. Selection of meteorological scenarios

Meteorological scenarios were determined using upper air data collected at McCarran International Airport (see Figure 1) for a 5-yr period, 1959–64. Especially, mixing depth and wind speed data were utilized for the lowest 20% of ventilation rates for the period; ventilation rate was determined as the product of mixing depth and the average wind speed through the mixing depth. For the above purpose, a 2-way contingency table involving wind speed and mixing depths was devised using this subset of the 5-yr data set for the fall and winter CO season in the local area. Six distinct scenarios representing combinations of wind speed and mixing depth, which constitue 94% of the data, were chosen from the contingency table.

It should be noted that other techniques for categorization of meteorlogical situations were attempted which in each instance provided poor results. For instance, statistical analysis of geopotential height data on 850 milibar (mb) charts for the eastern Pacific and western United States was accomplished in the manner outlined by Lund (1963) and Roach and McDonald (1975). However, the classes selected were not usually relatable to distinct features on ground level weather charts, and a large percentage of charts could not be placed into discernible classes. Better results might be attained if ground level data were utilized, but such data were not readily available for computer processing. Consequently, meteorological situations were grouped into classes through visual examination of historical ground level weather charts, available on microfilm. Comparisons between the resulting synoptic meteorological patterns or classes and the ventilation rates were subsequently made using discriminant analysis (Meyers, 1971; Hoel, 1962). However, few groupings were statistically significant at the standard five percent level. It is likely that pollutant transport and diffusion are determined by the details of atmospheric circulations which may not be readily divisible by a classification scheme based fundamentally upon synoptic scale weather features.

4.2. The first step – identification and ranking of potential monitoring sites

For this purpose, the SAI Model was exercised for each of the six meteorological scenarios. In this case, carbon monoxide concentration fields spanning 13 hours, at hourly intervals between 7 : 00 a.m. and 8 : 00 p.m., Local Standard Time (LST) were determined. The corresponding FOM fields were subsequently computed using the following expression:

$$\mathrm{FOM}(x, y) = \sum_{K=1}^{6} \begin{pmatrix} \text{Concentration at location} \\ (x, y) \text{ under meteorological} \\ \text{pattern k} \end{pmatrix} \cdot \begin{pmatrix} \text{Probability of} \\ \text{meteorological} \\ \text{pattern } k \end{pmatrix} . \quad (1)$$

An algorithm developed for identifying potential monitoring sites was used for searching for the highest values in the FOM field. This algorithm eliminates locations having high FOMs that are adjacent to locations having higher FOMs without an intervening

trough. Such locations are considered to be adequately represented by the adjacent location having the higher FOM value. The isolated peaks of the FOM thus selected are chosen as potential candidates for monitoring stations. Because the NAAQS for CO have been specified as 1-hr and 8-hr averages, computations for the FOM were carried

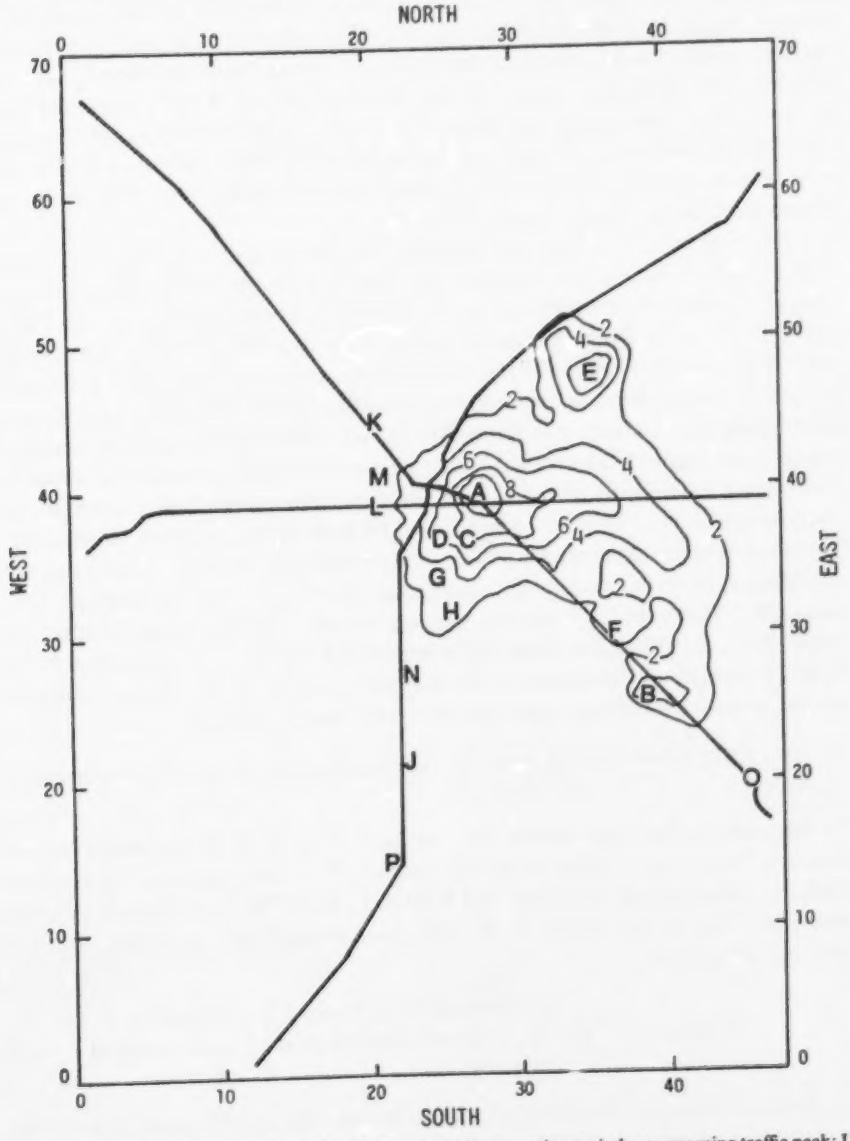

Fig. 5. Ranked monitoring locations for CO based on 1-hr averaging period near morning traffic peak: Las Vegas Valley.

out for each hour from 7:00 a.m. through 8:00 p.m and for the two 8-hr periods near the morning and evening trafic peaks. These periods represent the highest CO concentrations either observed or predicted in the Las Vegas area because of the dominant contribution of automotive emissions. The resultant FOM distributions for the following time periods are shown in Figure 5, 6, and 7:

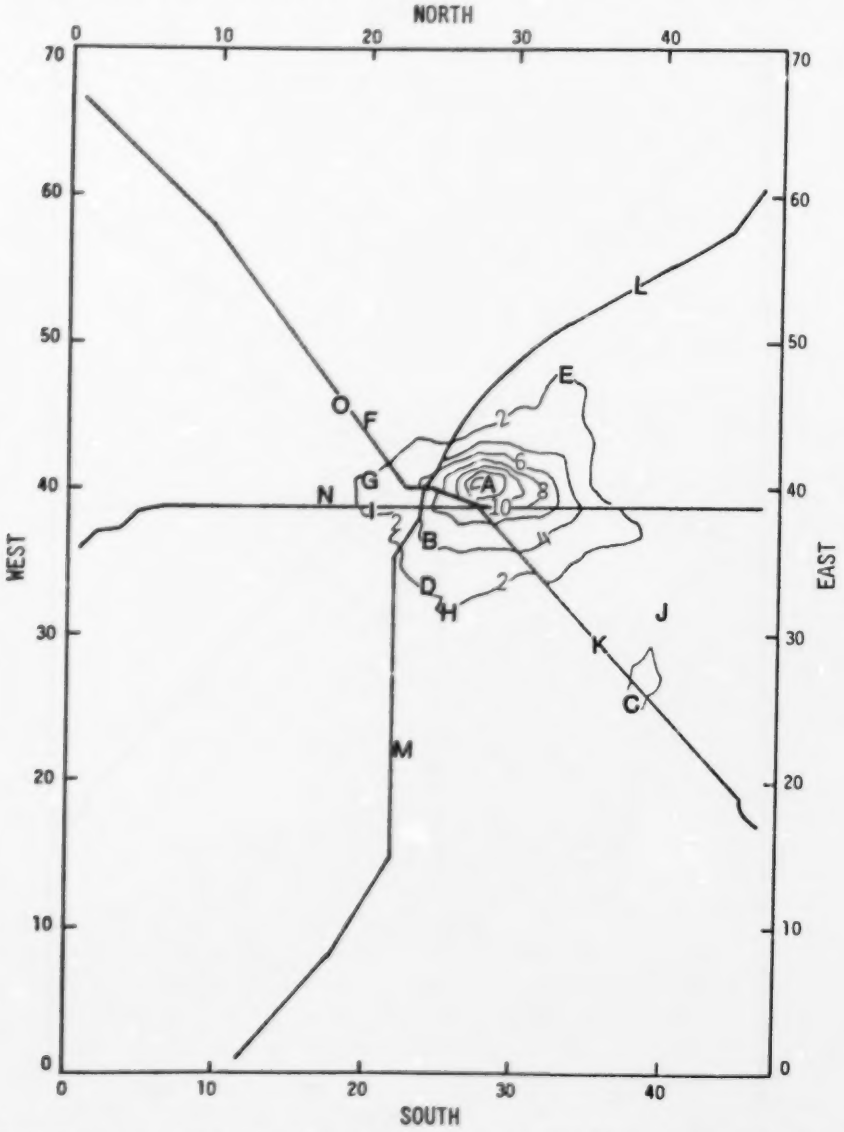

Fig. 6. Ranked monitoring locations for CO based on 1-hr averaging period near evening traffic peak: Las Vegas Valley.

– 1-hr period near the morning traffic peak (7 : 00 a.m.).
– 1-hr period near the evening traffic peak (6 : 00 p.m.).
– 8-hr period near the evening traffic peak (12 : 00 to 8 : 00 p.m.).

In these figures, isopleths for the FOM (in ppm) overlay the selected monitoring locations. The locations are ranked alphabetically according to the magnitude of the

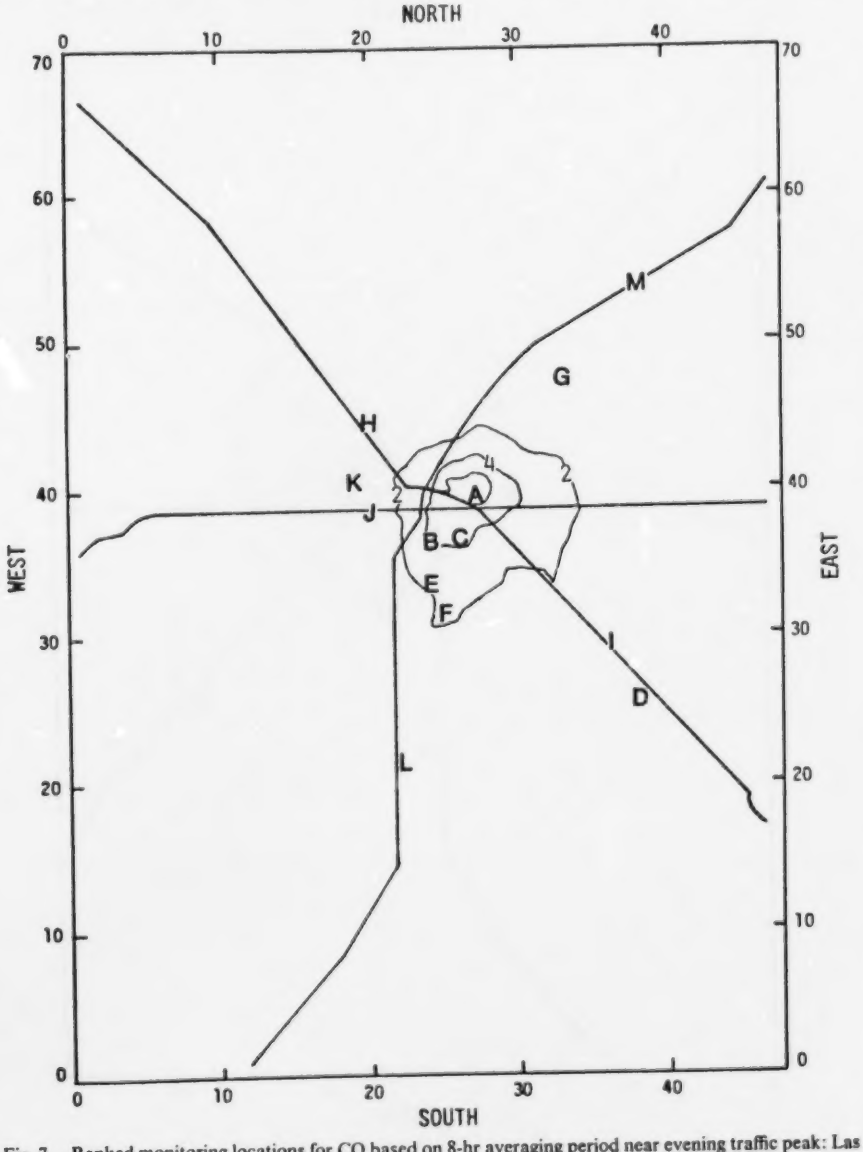

Fig. 7. Ranked monitoring locations for CO based on 8-hr averaging period near evening traffic peak: Las Vegas Valley.

FOM. Consequently, a total of more than 40 monitoring stations were identified and ranked. A perusal of these selected monitoring stations shows a pattern of proximity to major Las Vegas roadways, a fact that is not too surprising since traffic is the major emission source for CO. It is, however, interesting to note that all three sets of calculations identify a location in the vicinity of an existing station on East Charleston (see Figure 1), a location that usually reports the highest CO concentrations in Las Vegas. The 1-hr morning maximum (Figure 5) identified locations at Henderson and downtown Las Vegas as the second- and third-ranked locations, whereas the 1-hr evening maximums (Figure 6) identified the same two locations, but in reverse order. The finding is probably due to the fact that Las Vegas morning traffic is job-related, whereas the evening traffic is primarily caused by visitors in the downtown area. This result seems to indicate that the FOM methodology developed under the present project can indeed detect subtle diurnal variations in an emissions pattern that may be unique to the Las Vegas area. In the next subsection, an optimum monitoring network for metropolitan Las Vegas is established from among these stations by statistically determining the minimum number of monitoring stations required.

4.3. The Second Step – Determination of the Minimum Number of Stations Required

The determination of the optimum network configuration or the minimum number of monitoring stations required is accomplished by computing the SOI for each of the ranked monitoring locations. The SOI distributions are, in turn, determined by the spatial correlation coefficients and the associated cutoff values for a prescribed confidence level.

Concentration fields for the six meteorological scenarios determined by the model simulation provide the data base for evaluating the spatial correlation coefficients for each of the monitoring locations identified. Prior to the calculation of the spatial correlation coefficients, a smoothing of these concentration fields was accomplished to remove small-scale fluctuations. Similar operations are commonly used in turbulence research and numerical weather prediction (Shuman, 1957, and Haltiner 1971). Smoothing in this study was accomplished by the following operation: Assuming that $C^g_{x,y}$ is the gth time-smoothed concentration at grid point (x, y), then the $(g + 1)$-th time-smoothed concentration field is obtained by

$$C^{g+1}_{x,y} = \frac{C^g_{x,y} + b\overline{C}^g_{x,y}}{1 + b} \tag{2}$$

where

$$\overline{C}^g_{x,y} = \frac{1}{4}\left[C^g_{x-1,y} + C^g_{x+1,y} + C^g_{x,y-1} + C^g_{x,y+1}\right],$$

and b is a weighting factor to be empirically determined. A value of 2 was chosen for b, which is comparable to the well-known two-dimensional Shuman filter (Nelson and Weible, 1980).

In the present application, three smoothing operations were sufficient to facilithate further analysis without altering the essential features of the original concentration fields. The data base thus consists of 13 hourly smoothed concentration fields for each of the 6 meteorological scenarios for a total of 78 samples. Several values of the cutoff sample correlation coefficients to ensure specific minimum values are imposed. The corresponding population correlation coefficient and the variation explained as numerically determined from Table II of Liu *et al.* (1986) for a sample of size of 78 at 95 percent confidence level are shown in Table II.

To demonstrate the utility of the siting methodology, a total of 19 monitoring locations was selected from the highest ranking FOM monitoring locations. The 13 highest ranking locations, determined by the 8-hr average concentration distributions FOM for the evening traffic peak, were augmented by three locations each from the highest ranking 1-hr averages for the morning and evening traffic peaks, which were not adjacent to the locations already selected. The 19 stations were selected to cover maximum or peak concentrations.

TABLE II

Cut-off sample correlation coefficient to ensure minimum values for population correlation coefficient and variance explained at 95% confidence level with 78 samples

Sample correlation coefficient cut-off value r_c	Population correlation coefficient minimum value ρ_c	Variation explained coefficient minimum value ρ_c^2
0.4	0.18	0.03
0.5	0.30	0.1
0.6	0.44	0.2
0.7	0.56	0.3
0.8	0.70	0.5
0.9	0.85	0.7

In addition, as a further demonstration of the methodology for secondary monitoring objectives discussed earlier, three stations located in the northern, western, and southeastern outskirts of the city were arbitrarily added to measure either the background or baseline air quality in the Las Vegas area. The locations and characterizations of these 22 candidate stations are listed in Table III.

As described in the companion paper to this article (Liu *et al.*, 1986) the SOI is dictated by the cutoff correlation coefficient. Assuming that the criterion for an optimum network design is based on its capability to catch at least 50% of the concentration variations 95% of the time, then Equation (9) of that paper yields a minimum value of 0.7 for ρ_c.

With a sample size of 78, Table II shows that this value of ρ_c corresponds to a cutoff sample correlation coefficient of 0.8. Therefore, this value was used to determine the

TABLE III

Identification of potential monitoring locations in the Las Vegas valley

Station identification	*x*-coordinate	*y*-coordinate	comments
A	28	40	Locations determined by 8-hr figure-of merit near the evening traffic peak.
B	25	37	
C	27	37	
D	39	26	
E	25	34	
F	26	32	
G	34	48	
H	21	45	
I	37	30	
J	21	39	
K	20	41	
L	23	22	
M	39	54	
N	41	32	Locations determined by 1-hr figure-of-merit at the evening traffic peak.
O	18	40	
P	19	46	
Q	23	48	Locations determined by 1-hr figure-of-merit at the morning traffic peak.
R	46	20	
S	22	15	
T	4	37	Arbitrarily chosen rural locations.
U	28	60	
V	43	15	

spheres of influence for each of the 22 stations listed in Table II. Stations were deleted from the list if the individual areal coverage, after eliminating overlapping regions already covered by higher-ranking stations, was less than 10% of the coverage of the highest-ranked station. As a result, a total of 10 air quality monitoring stations was identifed, among which 3 are rural background stations. The locations of these 10 stations and their joint areal coverage (shaded areas) are shown in Figure 8. For each of the stations, the following statistics were compiled to measure the effectiveness of individual stations as well as that of the overall network:

- The fraction of area covered by the individual station based on the total area considered (48 × 70 km = 3360 km^2), as determined by SOI.
- The cumulative areal coverage, expressed as the fraction of the total area considered, beginning with the highest-ranked station.

These summary statistics are tabulated in Table IV.

As a sensitivity test of the siting methodology, identical computations were made using a cutoff sample correlation coefficient of 0.5. This network configuration and its corresponding joint areal coverage (shaded areas) are presented in Figure 9. A total of 7 air quality monitoring stations were selected by the siting methodology. Among these stations, 2 are rural background stations. Summary statistics for the 7-station network

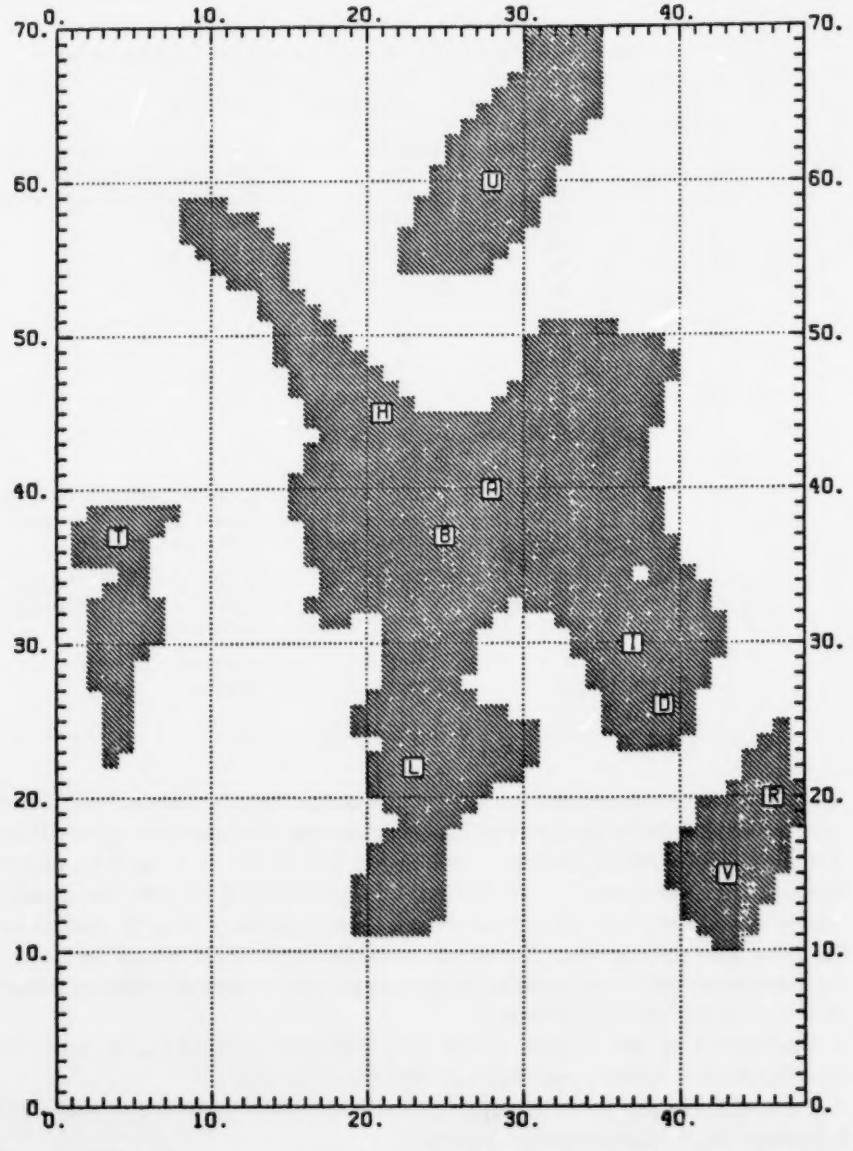

Fig. 8. An optimum air quality monitoring network for Las Vegas Valley based on a cutoff sample spatial correlation coefficient of 0.8.

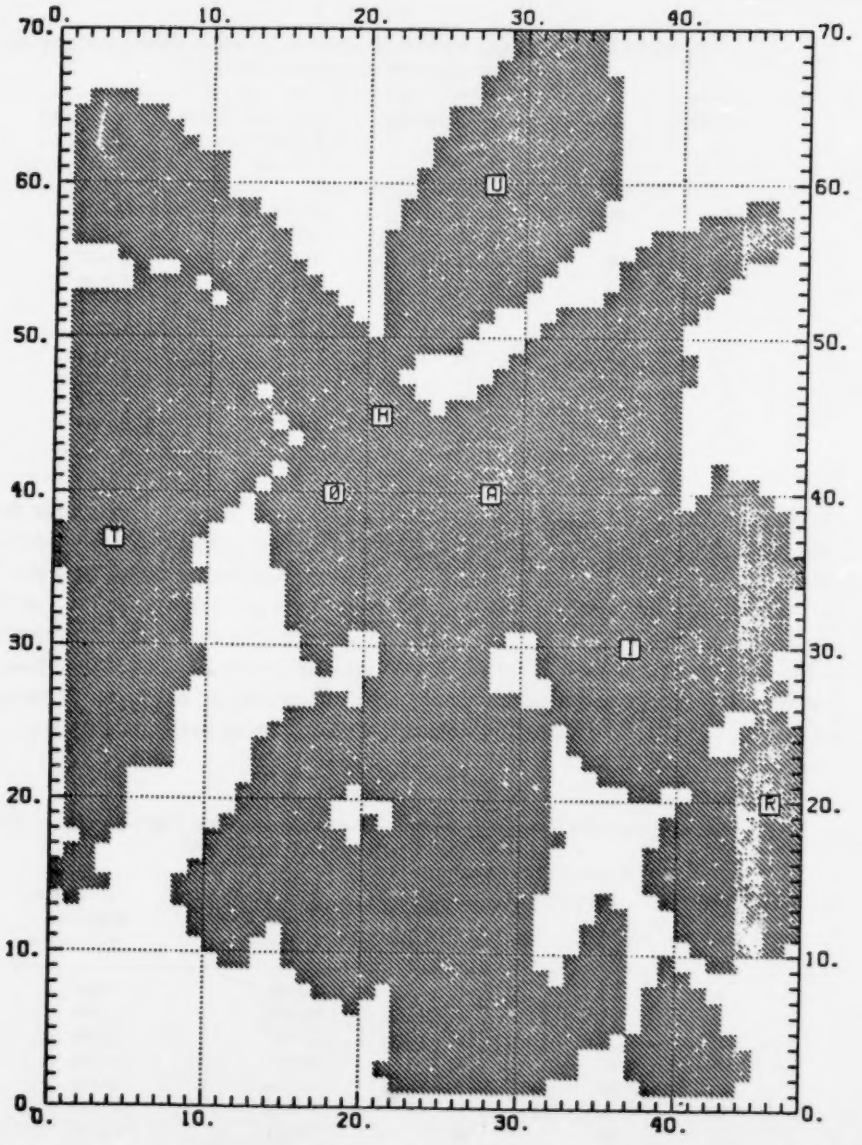

Fig. 9. An optimum air quality monitoring network for Las Vegas Valley based on a cutoff sample spatial correlation coefficient of 0.5.

TABLE IV

Summary statistics for selected monitoring stations in Las Vegas Valley based on a cutoff sample spatial correlation coefficient of 0.8

Station	*x*-coordinate	*y*-coordinate	Individual station fractional areal coverage	Cumulative fractional areal coverage
A	28	40	0.0723	0.0723
B	25	37	0.0253	0.0976
D	39	26	0.0455	0.1432
H	21	45	0.0155	0.1586
I	37	30	0.0122	0.1708
L	23	22	0.0211	0.1920
R	46	20	0.0104	0.2024
T	4	37	0.0182	0.2205
U	28	60	0.0336	0.2542
V	43	15	0.0119	0.2661

statistics for the 7-station network are given in Table V. It is interesting to note that cumulative areal coverage increases from 26.6% of the total region for the 10-station network to 62.3% for the 7-station network. However, it should be noted, as is shown in Table II, that the 7-station network can only detect a minimum of 10% of the concentration variations, whereas the 10-station network can detect a minimum of 50% of the concentration variations for the area within the combined spheres of influence (see Figures 8 and 9). In both cases, background stations could, of course, be deleted for a monitoring network with the sole purpose of discerning peak concentrations.

TABLE V

Summary statistics for selected monitoring stations in Las Vegas Valley based on a cutoff sample spatial correlation coefficient of 0.5

Station	*x*-coordinate	*y*-coordinate	Individual station fractional areal coverage	Cumulative fractional areal coverage
A	28	40	0.2604	0.2604
H	21	45	0.0664	0.3268
I	37	30	0.0327	0.3595
O	18	40	0.0429	0.4024
R	46	20	0.0354	0.4378
T	4	37	0.1232	0.5610
U	28	60	0.0622	0.6232

Further observations can be made concerning these monitoring networks as determined by the siting methodology:

– As shown in Figures 8 and 9, all urban stations chosen are located, as expected, along the main transportation corridors that constitute the bulk of carbon monoxide emission

sources (about 80%) in the Las Vegas area. Such stations correspond to the 'street canyon' and 'traffic corridor' stations referred to by Ludwig *et al.* (1976) and the 'A'-type stations referred to by Ott (1975).

– The joint areal coverage of these stations (as shown in Figure 8 and 9) tends to shift toward the east, southeast, and south of the major emissions sources, apparently reflecting prevalent local wind directions in Las Vegas for the meteorological scenarios identified.

– The western and northern rural background stations designated as stations T and U, were selected in both networks presumably because air quality in the neighborhood of these sites is not significantly affected by the major emission sources in the metropolitan Las Vegas area.

5. Concluding Remarks

As we discussed earlier, CO concentrations in the vicinity of major sources and in built-up portions of urban areas can have a natural variability on the order of tens of meters. The methodology here considered a resolution of a 1 × 1-km grid cell. An important aspect of future research efforts should thus be concerned with the development of a microscale analysis procedure for pinpointing the optimal location of a monitor within such a grid cell.

Also, the use of an air quality simulation model to generate a data base for the network design methodology facilitates its potential application both in areas with little or no existing air quality monitoring information and in areas with considerable future growth in emissions. Thus, the methodology could be used to redesign existing networks as well as design new networks.

6. Acknowledgements

L. M. Dunn, A. M. Pitchford, and P. N. Lem were largely responsible for the implementation and conduct of the field program. N. T. Fisher supervised the statistical processing of data for the program. Assistance in the field program was also furnished by the Clark County Health Department and the Nuclear Support Office, National Weather Service, Las Vegas, Nevada. This research was supported under U.S. Environmental Protection Agency Contract No. 68-03-2446.

References

Ames, J., Meyers, T. C., Reid, L. E., Whitney, D. C., Golding, S. H., Hayes, S. R., and Reynolds, S. D.: 1978, 'The Users Manual for the SAI Airshed Model', Systems Applications, Inc., San Rafael, California. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina under Contract No. 68-02-2429.

David, F. N.: 1938, *Tables of the Ordinates and Probability Integral of the Distribution of the Correlation Coefficient in Small Samples*. The Biometrika Office, Cambridge University Press, Cambridge, England.

Haltiner, G. J.: 1971, *Numerical Weather Prediction*, John Wiley and Sons, Inc., New York. New York.

Hoel, P. G.: 1962, *Introduction to Mathematical Statistics*, 3rd Edition. John Wiley and Sons, Inc., New York.

Johnson, W. B., Ludwig, F. L., Dabberdt, W. F., and Allen, R. J.: 1973, 'An Urban Diffusion Model for Carbon Monoxide', *J. Air Pollut. Control Assoc.*, **23**, 490–498.

Koch, R. C. and Thayer, S. D.: 1972, 'Validity of the Multiple Source Gaussian Plume Urban Diffusion Model Using Hourly Inputs of Data', In *Proceedings of Conference on Urban Environmental and Second Conference on Biometeorology*, Phyladelphia, Pennsylvania, 64–68.

Liu, M. K., Whitney, D. C., and Roth, P. M.: 1976a, 'Effects of Atmospheric Parameters on the Concentration of Photochemical Air Pollutants', *J. Appl. Meteorol.* **15**, 829–835.

Liu, M. K., Whitney, D. C., Seinfeld, J. H. and Roth, P. M.: 1976b, 'Continued Research in Mesoscale Air Pollution Simulation Modeling, Vol. I – Assessment of Prior Model Evaluation Studies and Ananlysis of Model Validity and Sensitivity', EPA-600/4-76-016A, U.S. Environmental Protection Agency, Research

Liu, M. K. and Yocke, M. A.: 1980, 'Siting of Wind Turbine Generators in Complex Terrain', *J. Energy* **4**, 10–16.

Triangle Park, North Carolina.

Liu, M. K., Behar, J. V., McElroy, J. L., Avrin, J., and Pollack, R. I.: 1986, 'Methodology for Designing Air Quality Monitoring Networks: I Theoretical Aspects', *Environmental Monitoring and Assessment* **6**, 1–11.

Ludwig, F. L., Berg, N. J., and Hoffman, A. H.: 1976, 'The Selection of Sites for Air Pollutant Monitoring', Paper presented at the 69th Annual Meeting of the Air Pollut. Control Assoc., Portland, Oregon.

Lund, I. A.: 1963, 'Map-Pattern Classification by Statistical Techniques', *J. Appl. Meteorol.* **2**, 56–65.

McElroy, J. L., Behar, J. V., Dunn, L. M., Lem, P. N., Pitchford, A. M., Fisher, N. T., Liu, M. K., Jerskey, T. N., Meyer, J. P., Ames, J., and Lundberg, G.: 1978, 'Carbon Monoxide Monitoring Network Design Methodology-Application in the Las Vegas Valley', EPA-600/14-78-053, U.S. Environmental Protection Agency, Las Vegas Nevada.

Meyers, J. P.: 1971, 'Discriminant Analysis in Laterite and Lateritic Soils and Other Problem Soils of Africa. An Engineering Study for Agency for International Development', AID/csd-2164.

Naylor, M. H.: 1984, Personal Communication. Director Air Pollution Control Division, Clark Co. Health District.

Nelson, S. P. and Weibel, M. L.: 1980, 'Three-Dimensional Shuman Filter', *J. Appl. Meteorol.* **19**, 464–469.

Ott, W. R.: 1975, 'Development of Criteria for Siting Monitoring Stations', Paper presented at 68th Annual Meeting of the Air Pollut. Control Assoc., Boston, Massachusetts.

Ott, W. R. and Thom, G. C.: 1976, 'A Critical Review of Air Pollution Index Systems in the United States and Canada', *J. Air Pollut. Control Assoc.* **26**, 460–470.

Reynolds, S. D., Roth, P. M., and Seinfeld, J. H.: 1973, 'Mathematical Modeling of Photochemical Air Pollution – I: Formation of the Model', *Atmos. Environment* **7**, 1033–1061.

Reynolds, S. D., Roth, P. M., and Seinfeld J. H.: 1974, 'Mathematical Modeling of Photochemical Air Pollution – III: Evaluation of the Model', *Atmos. Environment*, **8**, 563–596.

Roach, G. E., and MacDonald, A. E.: 1975, 'Map-Type Precipitation Probabilities for the Western Region', U.S. Department of Commerce, NOAA, NWS, Comm-75-10428.

Roth, P. M., Roberts, P. J. W., Liu, M. K., Reynolds, S. D., and Seinfeld J. H.: 1974, 'Mathematical Modeling of Photochemical Air Pollution – II: A Model and Inventory of Pollutant Emissions', *Atmos Environment* **8**, 97–130.

Shirr, C. C. and Shieh, L. J.: 1974, 'A Generalized Urban Air Pollution Model and Its Application to the Study of SO_2 Distributions in the St. Louis Metropolitan Area', J. Appl. Meteorol. **13**, 185–203.

Shuman, F. G.: 1957, 'Numerical Methods in Weather Prediction – II: Smoothing the Filtering', *Mon. Wea. Review* **85**, 357–361.

Slater, H. H. and Tikvart, J. A.: 1974, 'Application of a Multiple-Source Urban Model', in *Proceedings of 5th Meeting NATO/CCMS Expert Panel on Air Pollution Modeling*, Roskilde, Denmark, Chapter 14.

U.S. Environmental Protection Agency: 1976, 'Compilation of Air Pollutant Emissions Factors, AP-42, and Supplements 1 through 5, Second Edition'.